

**UC San Diego PISCES Program Grant Continuation  
Progress Report:**  
Plasma Boundary Science, Plasma Materials Interactions, and  
Collaborative Fusion Research

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## **Introduction**

The UC San Diego PISCES Program is a program of fundamental and applied experimental research in the field of boundary plasma science for fusion applications. The Program is organized into three principle research thrusts: (1) Physics of the plasma boundary region, (2) Plasma materials interactions science, (3) Plasma facing systems technology. The present report is the annual progress report for the first year, Jan. 1, 2001 to Dec. 31 2001, of the PISCES three year research grant.

In the following, we briefly summarize the PISCES program and plans, then provide brief descriptions of some of the most important research findings of the past year.

## **Summary of UCSD-PISCES Research Program**

The following Table, Fig. 1, summarizes the UCSD-PISCES research plan for FY02-FY04. As can be seen the PISCES research program supports a cross-section of US and international fusion program experiments and programs. US confinement experiments including DIII-D and NSTX are supported in the areas of carbon and boron material coating effects and plasma erosion phenomena. The US ALPS/ALIST/APEX programs are supported by fundamental plasma interactions experiments with liquid metals on the UCSD PISCES facility and through the development and testing of liquid lithium rail and belt limiters in collaboration with PPPL on the CDX-U torus.

During FY02 we will expand our interaction with PPPL on the CDX-U experiments with the new toroidal belt limiter and the present lithium rail limiter. In the attached budget we have requested incremental funding for a new junior level scientist to be stationed at PPPL in the second half of FY02. This new scientist would be responsible for day-to-day operations of the CDX-U facility and for data collection and analysis on the liquid lithium limiter experiments.

The US-Japan exchange program activities are continued in the areas of divertor physics, molecular processes, and tungsten materials studies. Fundamental plasma boundary interactions experiments on recombining divertor plasmas, plasma turbulence imaging, and related experiments are continued and two Ph.D. student thesis projects are underway on these topics.





## **Beryllium Decontamination of the PISCES-B Facility**

The PISCES-B facility, Fig. 2, was used throughout the US ITER-EDA project for plasma materials interactions experiments with beryllium containing materials. Beryllium material was, and is regarded by the ITER team as the leading candidate for the ITER chamber first wall surface. The PISCES-B experiments provided critical data on plasma erosion of beryllium that informed the ITER design. Perhaps the most significant finding of this work, beyond the basic erosion rate data, was the discovery and subsequent explanation of the conditions for spontaneous formation of carbonaceous coatings on solid beryllium.

During the ITER/EDA activity we operated PISCES-B in a controlled environment clean room chamber; scientists and engineering professionals carried out the beryllium operations using state-of-the-art safety procedures and protective equipment including full body suits, respirators, and breathing air supply lines. During the five years of beryllium operations, high safety standards were maintained and enforced. Through the efforts of our excellent safety minded personnel, and the excellent equipment and support from OFES, we completed the beryllium research from FY1995 through FY1999 without any beryllium hazard events.

During the past year, the US PFC community and OFES have reached agreement that the PISCES-B facility should be decontaminated and re-conditioned for non-beryllium operations. The rationale for decontamination is two fold, it will (1) reduce the ESH burden on the group and better conform to the ALARA standard, and (2) substantially increase the productivity of the PISCES-B facility for continuing PMI experiments. During the past year, the decontamination project, BEDCON, was reviewed by the US PMI community with input from experts from Sandia National Laboratory and other US laboratories. Subsequently, a project plan and project budget of \$200k were submitted to OFES and approved. The BEDCON project is scheduled to begin in January, 2002 and be completed in late spring/early summer of 2002. At the completion of the BEDCON project, the PISCES-B facility will be restarted for non-beryllium PMI experiments. Importantly, we will maintain, at little cost, the capability to re-start beryllium operations should they be needed in the future. The BEDCON project plan and budget were submitted separately to OFES and are not included in the budget pages of this report.

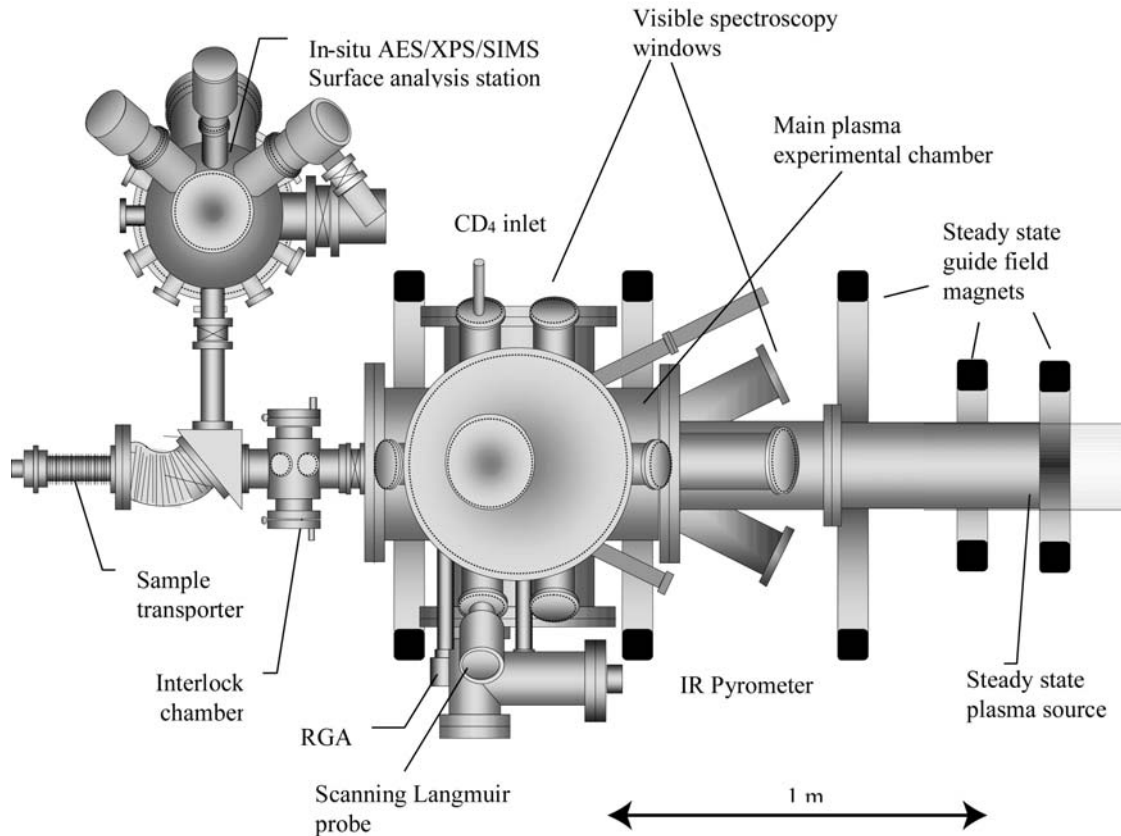


Fig. 2. PISCES-B facility is primarily dedicated to plasma materials interactions studies. It is housed in a controlled atmosphere clean room and is capable of handling materials such as beryllium and liquid lithium.

### International Collaborations

Collaborative experiments and other joint activities with US and international partners are a central element of the PISCES program. The long standing PISCES group involvement with the Japan National Institute for Fusion Sciences (NIFS) had developed into a collaborative program of boundary plasma molecular and atomic physics research with NIFS and Nagoya University and of materials interactions studies of tungsten, boron, and carbon with Kyushu University and NIFS. This work is carried out through bilateral exchanges under the US Japan exchange program.

Also in FY01 the PISCES group hosted Prof. Jorg Winter of University of Bochum, Germany as a visiting faculty member. Prof. Winter is an expert on plasma surface interactions and is working with Dennis Whyte of our group on the problems of boron coatings, and carborane processes for a period of four months.



## **Research Highlights FY2001**

The past year has been a very productive one for the PISCES Group, with a number of research thrusts yielding significant findings. Particularly noteworthy was the successful measurement of the hydrogen retention rate in liquid lithium and the surface recombination coefficient for hydrogen at the surface of liquid lithium. These two results are strongly indicative that a liquid lithium PFC will in fact provide a low recycling surface for fusion applications. In the following bullet list, we highlight other significant research findings and accomplishments from the PISCES Program. The list is divided among three research thrust areas: (1) Boundary plasma science, (2) Plasma materials interaction science, and (3) Plasma facing system technology.

### **FY01 Highlights in Boundary Plasma Science Research**

- Designed and constructed an improved omegatron mass spectrometer for studies of molecular ions  $H^+$ ,  $H_2^+$ , and  $H_3^+$  in detached hydrogenic plasmas and  $He^+$  and  $HeH^+$  in detached hydrogen-helium plasmas.
- Lisa M. Blush completed her Ph.D. thesis on the physics of the gaseous target divertor and detachment.
- Detected and quantified the presence of radially convected plasma structures in the boundary turbulent plasma. We call these radially convected events avaloids. This discovery is important as it identifies a new particle and energy transport mechanism in the outer plasma boundary. Similar structures are now being identified in tokamak boundaries.
- Continuing the mapping of the 2 and 3 dimensional turbulent flows in PISCES using the UCSD developed CAPPIS plasma flow imaging system.
- Continuing investigation of new diagnostics for molecular neutrals and ions including FTIR spectroscopy, Electron Beam Fluorescence Spectroscopy, and the advanced Omegatron.
- Carried out analysis of the magnetic boundary properties of the NCSX stellarator and participated in the physics design review.

### **FY01 Highlights in Plasma Materials Interactions Science Research**

- Measured the surface recombination rate for hydrogen in liquid lithium, Fig. 3. This result is significant because surface recombination appears to be the rate limiting processes for the release of hydrogen dissolved in liquid lithium. Hence,

it is essential for estimating the overall hydrogen removal effectiveness of liquid lithium PFC's.

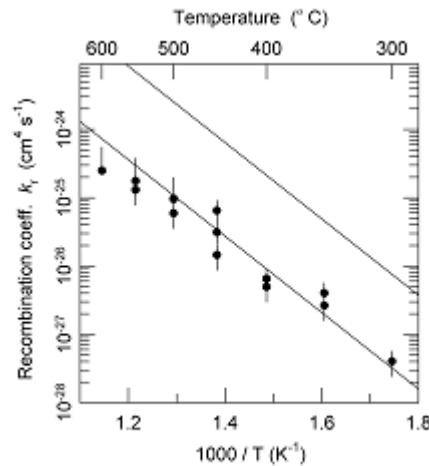


Fig. 3. Surface recombination rate coefficient for hydrogen in liquid lithium measured on PISCES-B.

- The hydrogen retention rate of liquid lithium was measured on PISCES-B over a range of hydrogen ion fluences and found to be essentially 100% limited only by the solubility phase boundary condition. This result is strongly indicative that a liquid lithium PFC will act as a low recycling surface until the solubility limit is reached.
- Measurements of hydrogen and helium permeation of liquid lithium have begun. The critical step of forming a high vacuum seal using liquid lithium was achieved.

#### **FY01 Highlights in Innovative Plasma Facing Systems Research**

- The liquid lithium rail limiter that UCSD built for the CDX-U experiment was operated successfully in the first part of the year and experiments were done identifying the formation of liquid lithium droplets (LLDs) generated by magnetic body forces.
- Carborane coating apparatus was deployed on PISCES-B and the boronization process using carborane working gas was found to be highly effective. Deposition rates 10-100 times faster than conventional boronization were achieved in PISCES.
- PISCES Group personnel participated in the engineering design of the CDX-U toroidal liquid lithium belt limiter. The limiter was installed during FY01 and is now being prepared for experiments.

## **Boundary Plasma Science**

### **Gaseous Recombining Divertor Experiments**

During the past three years, a thorough investigation of gaseous target divertor plasma processes has been carried out by our group. In FY2001 a Ph.D. Thesis was completed on this topic by our student Lisa Blush. The conclusions of this work were reported at the European Physical Society Meeting, (Madrid, 2001) and a journal article is in preparation. This thesis work thoroughly documented the conditions under which gas target plasma detachment occurs.

These experiments made use of a unique plasma plugged gas baffle arrangement in PISCES-A, Fig. 4, that allows a flowing plasma to interact with a gaseous target having a variable neutral pressure. Neutral target pressures ranging up to 40mT,  $n_{H_2} = 1.2 \times 10^{15} \text{ cm}^{-3}$  were achieved.

These experiments have shown that a sufficiently high neutral gas density can absorb the particle momentum and radiate the power entering the simulated divertor chamber in PISCES-A. In this situation, power and plasma fluxes are prevented from reaching the chamber wall directly and from being concentrated on a small strike zone. Having established the detached plasma conditions, the next series of experiments concentrated on establishing a better understanding of the importance of atomic and molecular collisions, radial transport, atomic line radiation to the detachment process.

### PISCES-A Gas Target Divertor Simulation Apparatus

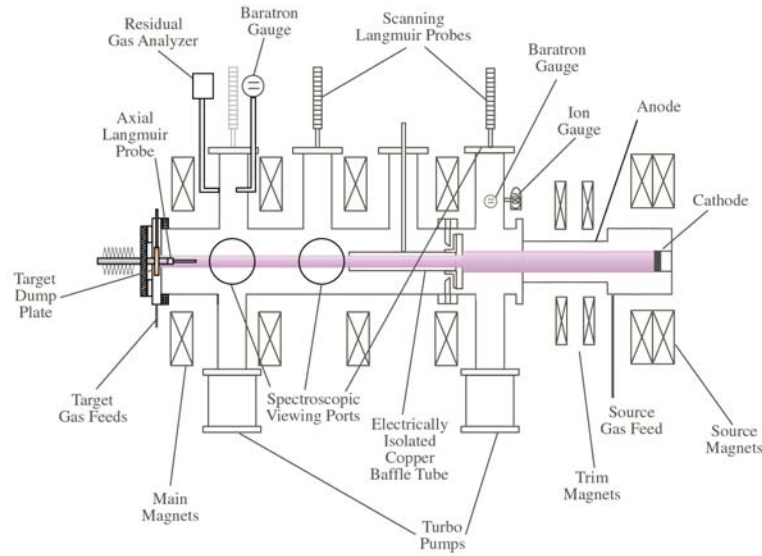


Fig. 4 The PISCES-A device with gas baffle tube and open gaseous divertor target region.

### **Particle and Power Balance Measurements of the Gas Target**

Because of its simple geometry and steady-state operation, the PISCES-A divertor simulator provides an ideal test-bed for performing total particle and heat balance measurements during gas-target detachment. Understanding of the mechanisms by which detached plasmas in PISCES-A can spread out the target heat load could be important for divertor designs in larger devices.

### **Progress in FY2001 includes:**

- Absolutely-calibrated Balmer emission measurements were carried out over a wide range of operating conditions.  $H\alpha$  over  $H\gamma$  ratios in the range of 15-25 were observed in the plasma core region which is consistent with dissociative excitation of  $H_2$  molecules. Dissociative excitation is expected to produce the predominant Balmer series emission in PISCES plasmas. Surprisingly,  $H\alpha$  over  $H\gamma$  ratios of 30 to 50 were seen in the cold plasma halo region. These ratios cannot be explained with expected ratios and could therefore indicate a novel molecular process, such as  $H_3^+$  recombination.
- Careful deconvolution of the Balmer emission from the plasma core indicates that the emission consists of a narrow, cold ( $T_H < 0.3$  eV) component and a broad warm ( $T_H \approx 5$

eV) component. The narrow component has been identified with dissociative excitation of  $H_2$ , while the broad component has been identified with dissociate excitation and/or dissociative recombination of  $H_2^+$  or  $H_3^+$ .

- Particle-balance experiments have been performed on hydrogen plasmas in PISCES-A. Total plasma particle sources and sinks were measured and found in balance to within a factor of  $\sim 2$ , as shown below. Surprisingly, the dominant sink term for fully detached plasmas (target pressures  $P_{target} > 25$  mTorr) is found to be flow to the side walls, indicating that extremely rapid radial transport is occurring in these experiments.

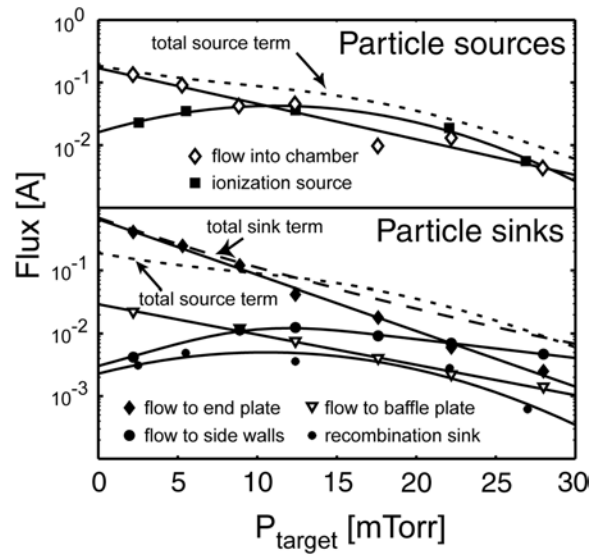


Fig. 5. Systematic measurements of particle sources and sinks as a function of gas target pressure on PISCES-A indicate the importance of radial transport in the particle balance.

## Advanced diagnostics, Atomic and Molecular Processes

### Omegatron mass spectrometer development

Plasma detachment in the PISCES-A divertor simulator is seen to be qualitatively similar to detachment in tokamak divertors, namely an order-of-magnitude or more decrease in plasma pressure is observed at high gas-target pressures (typically several mTorr or more). Although the molecular ion fraction could be high in these conditions, the role of molecular ions in plasma detachment has not been well understood. The PISCES-A omegatron mass spectrometer program is aimed at developing a molecular ion mass spectrometer for use in detached divertor conditions.

### Progress in FY2001 includes:

- The prototype UCSD omegatron (completed in FY2000) was installed and operated in the NAGDIS-II linear machine as part of the US-Japan collaboration by one of our scientists, Eric Hollmann. A 90% He, 10% H<sub>2</sub> working gas mixture was used; the resulting plasma was found to consist of roughly 50% He<sup>+</sup> and 50% H<sup>+</sup>, consistent with spectroscopy measurements. HeH<sup>+</sup> was not observed in the plasma core; this is consistent with the high core temperature measured with probes ( $T_e > 5$  eV), but inconsistent with the previous belief that HeH<sup>+</sup> - catalyzed recombination was responsible for the quenching of high pressure helium-hydrogen discharges in NAGDIS-II. Examples of mass spectra are shown below.

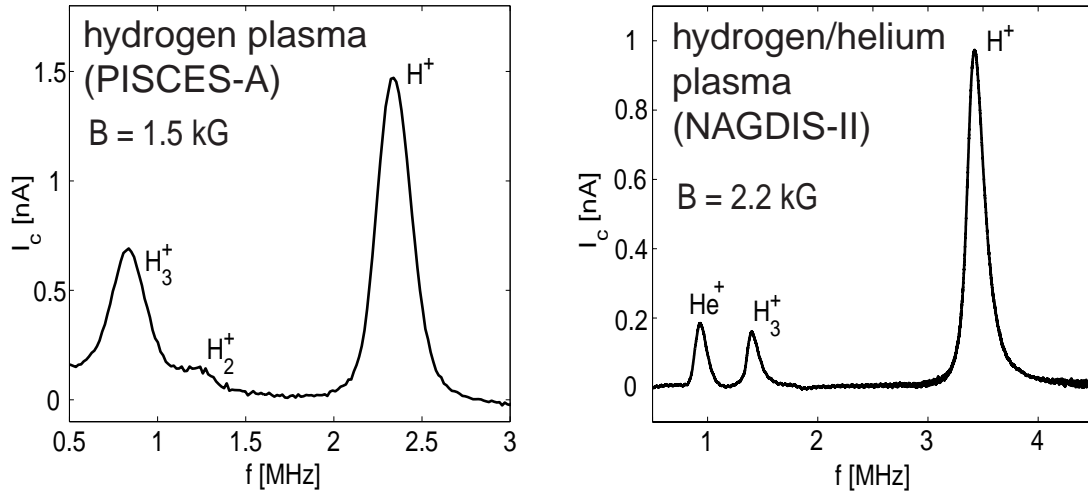


Fig. 6. Omegatron spectra from UCSD diagnostic used at Nagoya University.

- An orbit-tracing code was developed to simulate the relative characteristics of different rf chambers for an improved omegatron diagnostic. A clamshell-type rf chamber with an inside diameter of 3 cm and gap of 30° was chosen based on its good collection efficiency, reasonably good linewidth and ease of construction.
- The improved omegatron diagnostic has been constructed. In addition to the improved rf cavity design, it features the following improvements over the prototype UCSD omegatron: modular construction for easier assembly and disassembly, better differential pumping, an exchangeable entrance pinhole for operation at different plasma densities, and a bellows-mounted assembly for radial scanning of the diagnostic head.

### Measurement of N<sub>2</sub> Rotational Temperatures: Electron Beam Fluorescence

The rotational state of molecules can greatly influence the molecular reaction rates to processes such as dissociation, recombination, and others. Because of this, we have been

interested in diagnostic techniques to measure the rotational temperature of molecules in boundary plasmas. During FY01 one of our graduate students carried out exploratory experiments to develop the technique of electron beam fluorescence for these measurements.

In electron beam fluorescence, the intensities of each transition are a function of the population, rotational quantum number, and rotational temperature of the excited state. Rotational temperature of the neutral molecule is assumed to be equal to that of the resulting molecular ions because of the Franck-Condon principle. Since the rotational quantum numbers can be calculated, the measured photon/transition population yields the original ground-state rotational temperature of the molecules.

So far experiments have made use of a high pressure molecular gas cell, usually filled with  $N_2$ , as a test target for EBF measurements. Initial measurements were successful during the summer of FY01, and some of the spectral data and the inferred rotational temperature is shown below in Fig. 7a,b. We expect to develop this technique further in FY02 for application to PISCES plasmas where molecular neutral and ion species co-exist.

This work is done in a collaboration between the PISCES Group and with other researchers here at the Center for Energy research including G. Tynan and R. Cattolica.

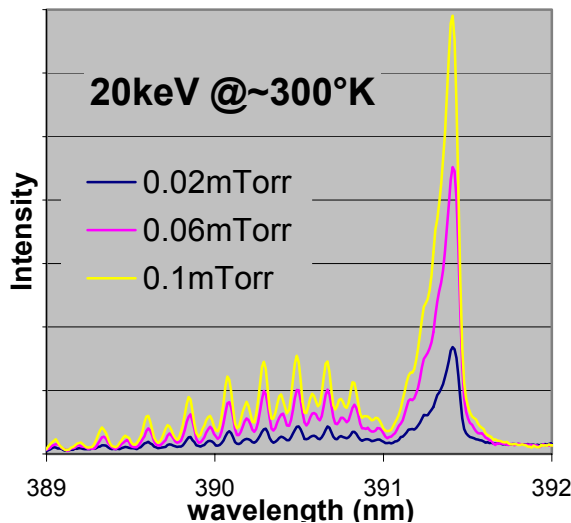


Fig.7a Nitrogen first negative spectra(~390nm).

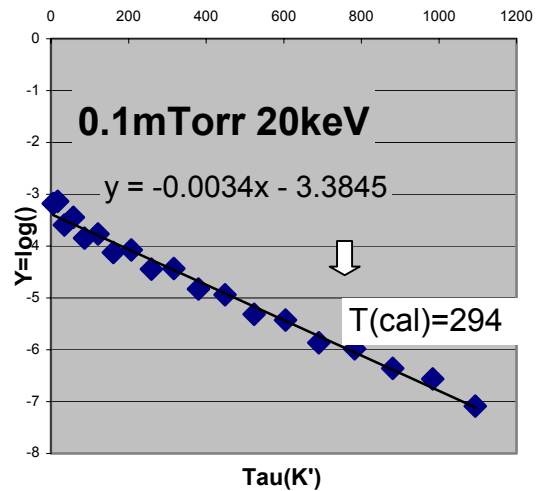


Fig.7b Rotational temperature obtained from line width analysis.

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## Infrared Spectroscopy

Because of the importance of molecular processes on material surfaces and in the boundary plasma, we have been increasingly interested in new diagnostics of these molecular states. One promising technique is IR spectroscopy. During the past year, we have built a small dedicated experiment to investigate Fourier Transform Infrared (FTIR) spectroscopy as a diagnostic of the molecular species. We were able to obtain an FTIR spectrometer on loan from PPPL through the PPPL/University Research Support Program. The apparatus is currently being setup as shown in Fig. 8 to search for IR spectral lines from molecules such as LiD in a plasma containing lithium.

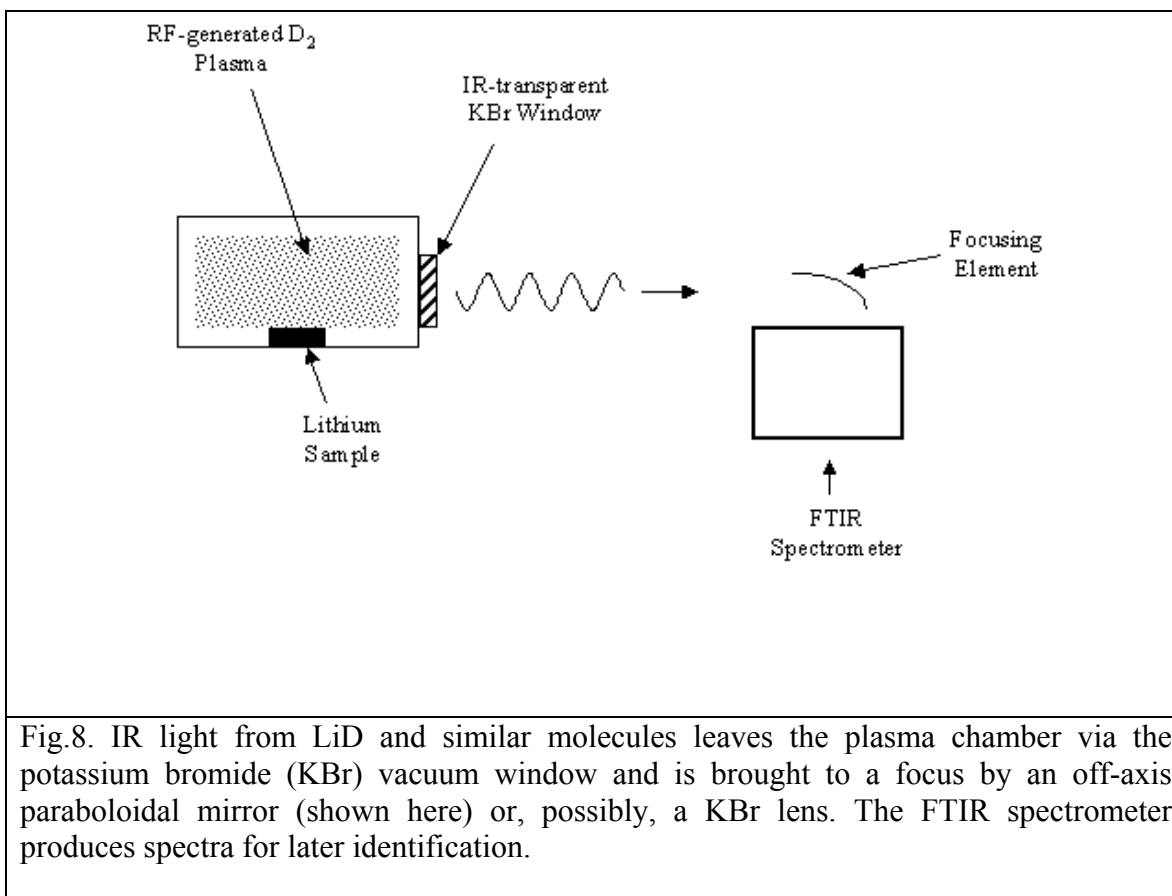


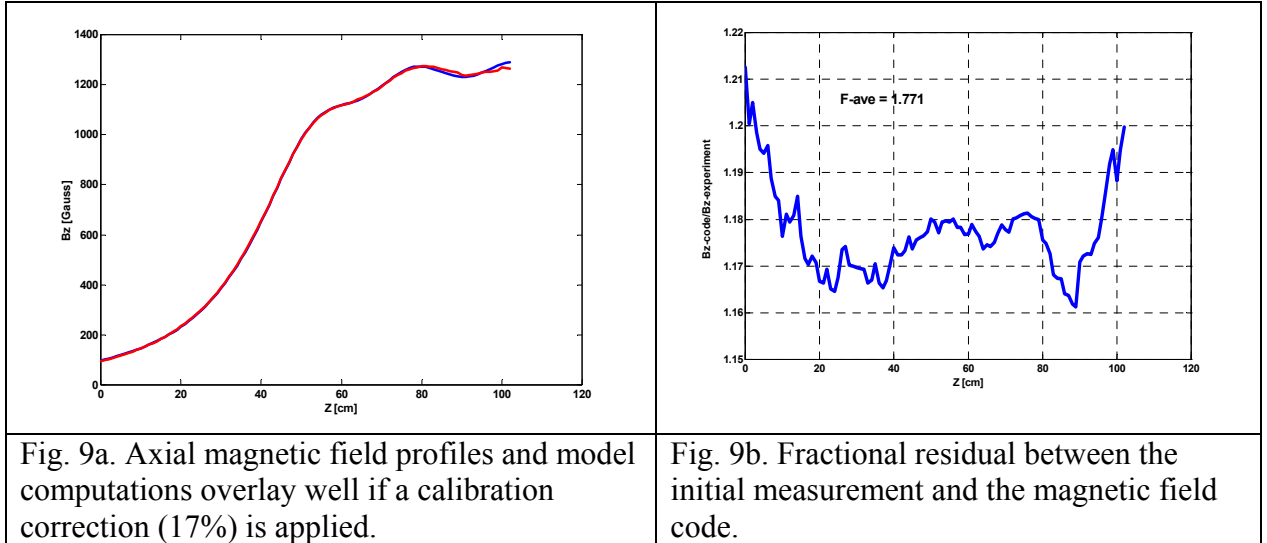
Fig.8. IR light from LiD and similar molecules leaves the plasma chamber via the potassium bromide (KBr) vacuum window and is brought to a focus by an off-axis paraboloidal mirror (shown here) or, possibly, a KBr lens. The FTIR spectrometer produces spectra for later identification.

## Magnetic Field Calibration of PISCES-A

Measurement of magnetic field in the PISCES-A linear plasma device is performed using a handheld Gaussmeter. The measurement is carried out along the axis of the PISCES-A cylindrical vacuum chamber. Magnetic field data in the axial direction are recorded and compared with computed values which are obtained by MATLAB magnetic modeling. The model calculation yields a field constant of 2.50 Gauss/Amp for PISCES-A, at  $z=100\text{cm}$ .



Fig. 9a,b shows the ratio between the experimental and model values. When the experimental values are multiplied by a factor of 1.17, they overlay the model values rather well. Because of this discrepancy and other problems related to instrumental calibration, we believe that our present Gaussmeter is inaccurate and has a calibration error. To solve this problem, we have purchased a more accurate Gaussmeter and calibration standard magnet, and plan to carryout more detailed comparisons during the last quarter of FY01.



## Turbulence and Transport in Boundary Plasmas

In the three-year PISCES Grant Proposal submitted and approved during FY00, we set ourselves the goal to elucidate the existence of convective transport in the scrape-off layer of magnetic confinement devices and to investigate its different properties and role with respect to diffusive transport. [1] We are pleased to report here, that an important part of this goal was achieved during the year 2001. Experiments carried out on PISCES-A were combined with data from toroidal devices on the topic of turbulent radial burst convection. Our findings were published in G. Y. Antar, et al., Phys. Rev. Lett., **87**, 6, 065001 (2001).

Our findings can be summarized in two major points:

- Convective transport in the scrape-off layer of magnetically confined devices exists in the form of plasma blobs, that we call avaloids, propagating radially and poloidally toward the wall. The radial velocities involved are of the order of few km/s and are clearly far from zero as it was assumed in many models when transport was considered to be only diffusive. This mechanism takes place in an intermittent way at a given point in space. Convective transport accounts for about 40% of the total radial transport. The figure below shows the ion saturation current profile as function of radius in PISCES. A zoom on one of the bursts is

also plotted. Notice that bursts can yield a plasma density at 2.5 cm from the edge comparable to the density in the center.

- Convective transport is universal in the sense that it can be observed in nearly all the linear and toroidal magnetic confinement devices. We demonstrated this for the first time by comparing the density fluctuations in PISCES, with plasma radius equal to 2.5 cm, to that of Tore Supra tokamak with minor radius of 75 cm. To illustrate our idea a zoom on one of the bursts recorded in the scrape-off layer of Tore Supra tokamak is plotted along with the one obtained on PISCES. The similarity of the two signals coming from PISCES and Tore Supra was confirmed statistically by comparing, among other things, the histograms, the power spectra and the conditional averaging.

Our future effort is now concentrated on the origin of avaloids in different magnetically confined devices. Imaging techniques developed in collaboration with S. Zweben (PPPL) and A. Liebsher (UCSD) will be used. This is in addition to the Langmuir probe measurements. Other than PISCES, the collaboration with B. LaBombard (CMOD-MIT) and P. Devynck (Tore Supra-Cadarache) and S. Zweben (NSTX-PPPL) is aimed at applying more or less the same ideas to the signals in order unveil whether avaloids have the same origin in these devices. A long term goal once the origin of convective transport is made clear, is to try to control this process by applying for example an electric field.

## References

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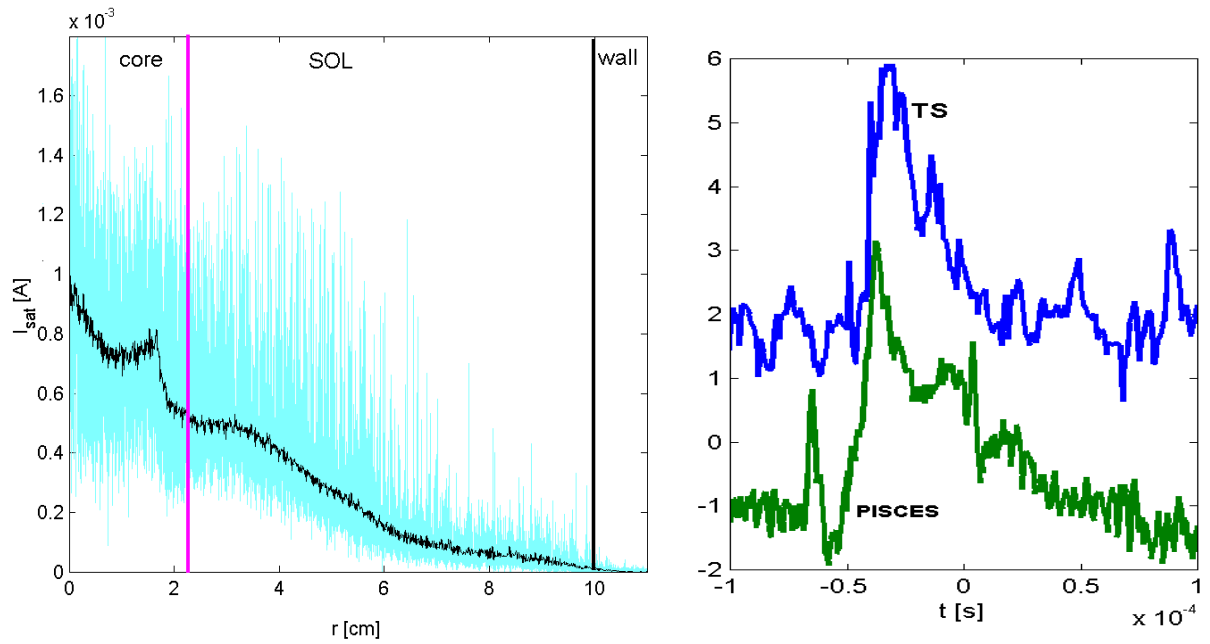


Fig. 10. This left-hand figure shows the ion saturation current as function of the radius of the probe. Notice that plasma exists all the way until the vessel wall. Although the average density decreases, spikes can give rise to density outside the plasma as high as inside the plasma. The left-hand plot shows a comparison of the ion saturation signal during the burst in PISCES and Tore Supra.

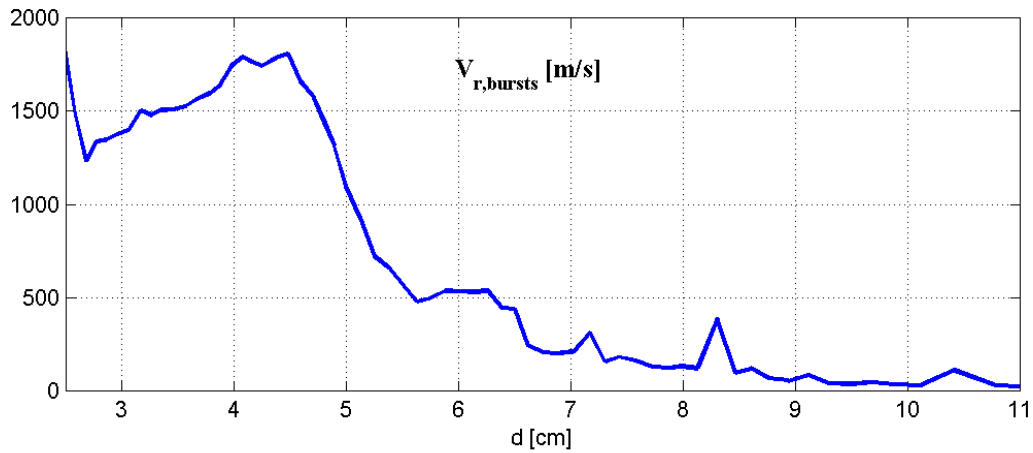


Fig. 11. This figure shows the radial velocity of the avaloids outside the main plasma in PISCES demonstrating that it is far from being negligible.

## Two-Dimensional Imaging of Plasma Fluctuations

The present generation of plasma density diagnostics by and large is limited to point or multi-point local measurements. At PISCES we have been carrying out a program to develop full two dimensional images of the plasma density distribution. One aspect of this has been the development of a novel plasma flux imaging system as part of the Ph.D. thesis of Mr. Andreas Liebscher. The plasma imager is called the Cathodoluminescent Phosphor Plasma Imaging System (CAPPIS). The CAPPIS system was deployed on PISCES-A and is now producing high quality imaging data.

Fig. 12 shows an example of a CAPPIS two dimensional images of the plasma density distribution and its fluctuations. These data were cross-checked with Langmuir probe diagnostics, and good agreement was found, [ A. Liebscher, *Rev. Sci. Instrum.* **72** (2001) 953 ]. A recent contribution from this diagnostic is that the correlation of plasma density fluctuations with emitted turbulent phosphor light has provided evidence for the presence of coherent modes and rotation in the PISCES-A linear plasma device. The development and improvement of the diagnostic has benefited greatly from interaction and collaboration with Dr. Stewart Zweben of the Princeton Plasma Physics Laboratory (PPPL), and technical information obtained from industry contacts involved in the latest development of inorganic phosphors.

## Imaging diagnostic development

Substantial progress in our understanding and characterization of the imaging diagnostic has enabled us to obtain high brightness images having time resolution in the few microsecond range. Further development and improvements of the imaging diagnostic are currently underway, and the following summarizes our achievements and future goals.

### Imaging Diagnostic

- **Image Optimization Code:** Development of a real time image optimization code using LabVIEW, MATLAB, and IMAQ Vision, has been completed. The code enables the frame capture software to process the statistical properties of the first few acquired image fields and reset internal hardware reference levels for maximum dynamic range. The acquisition program then permits continuous capture of 45 sequential optimized fields.
- **Phosphor Characterization:**

#### Ultraviolet Photoluminescent Apparatus

To obtain accurate phosphor decay time measurements a special apparatus has been completed employing an ultraviolet ( $\lambda = 370$  nm) LED source and fast (10 MHz) photodiodes. The present design enables us to measure phosphor decay times down to 100 ns. Knowledge of the exact persistence time determines the frequency response of the imaging diagnostic. In addition a

well-known fact is that the luminous efficiency is temperature dependent and this device was successfully used to characterize the photoluminescent temperature dependence of the ZnO:Zn phosphor emulsion.

#### Cathodoluminescent Electron Gun Calibration

A new e-beam source has been designed for absolute cathodoluminescent phosphor calibration. The e-beam is under construction and when completed will provide valuable information on the exact current and energy dependence of the imaging phosphor luminance. A novel cathode and electrostatic lens arrangement will produce high current density e-beams at selectable electron energies for our range of interest from 3-100 eV. In pulsed operation the device will also provide decay time values under electron bombardment.

- **New Phosphor Emulsion:** An improved inorganic ZnO:Zn [1024-01] phosphor emulsion with substantially shorter persistence time  $\tau_p = 400$  ns has recently been developed and will replace the previous imaging emulsion. This change will increase the frequency response of the CAPPIS diagnostic to 2.5 MHz. As a result the intensified CCD imaging camera will be able to capture plasma images on shorter time scales, and improve our understanding of the fast turbulent plasma fluctuations.

#### Experimental Plasma Imaging Results

- **Electron Density Profiles:** Measurement of the two dimensional radial plasma density profiles has verified the imaging diagnostic technique. The comparison of radial intensity profiles from calibrated phosphor images are in agreement with electron densities determined from Langmuir probe measurements. The spatial resolution  $k_\theta \leq 2\pi \text{ mm}^{-1}$  of the diagnostic has resulted in  $1 \mu\text{s}$  plasma images with a spatial resolution of  $1 \text{ mm}^2$ , and we find that spatial plasma density fluctuations of amplitude  $\tilde{n}/n > 1\%$  can be detected.
- **Coherent plasma modes:** Through the correlation of local turbulent phosphor light fluctuations with time series Langmuir probe data we have found the presence of coherent modes. A new technique will be tested in which time series phosphor light is captured in conjunction with each plasma image. Knowledge of the fundamental coherent mode frequencies will in principle permit the phase sorting of images from information contained in the time series data. This process will then produce clear two-dimensional images containing radial and poloidal information of the coherent modes.
- **Plasma rotation and shear:** Analysis of the CAPPIS image intensity distribution in combination with correlation measurements has provided information on the existence of plasma rotation and shear at the plasma edge. The results have been independently verified using spectroscopic techniques to

measure Doppler shift profiles and a newly developed DC emissive probe to examine the radial electric field.

The accomplishments in the development and experimental application of the CAPPIS diagnostic have resulted in high-resolution plasma images providing a better understanding of the two-dimensional plasma structure and fluctuations in PISCES-A. In the continuation of the imaging research focus on image analysis techniques will play an important role in understanding the relevant physics information contained in an image. Also, future implementation of the CAPPIS diagnostic in the edge of fusion devices is envisioned.

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A. Liebscher, S. Luckhardt, G. Antar, and S. Zweben, A Fast Phosphor Imaging Diagnostic for Two-Dimensional Plasma Fluctuation Measurements, Rev. Sci. Instrum. **72**, 953 (2001).

Investigators: A. Liebscher, G. Antar, and S. Luckhardt, UC San Diego, CER  
S. Zweben Princeton Plasma Physics Laboratory

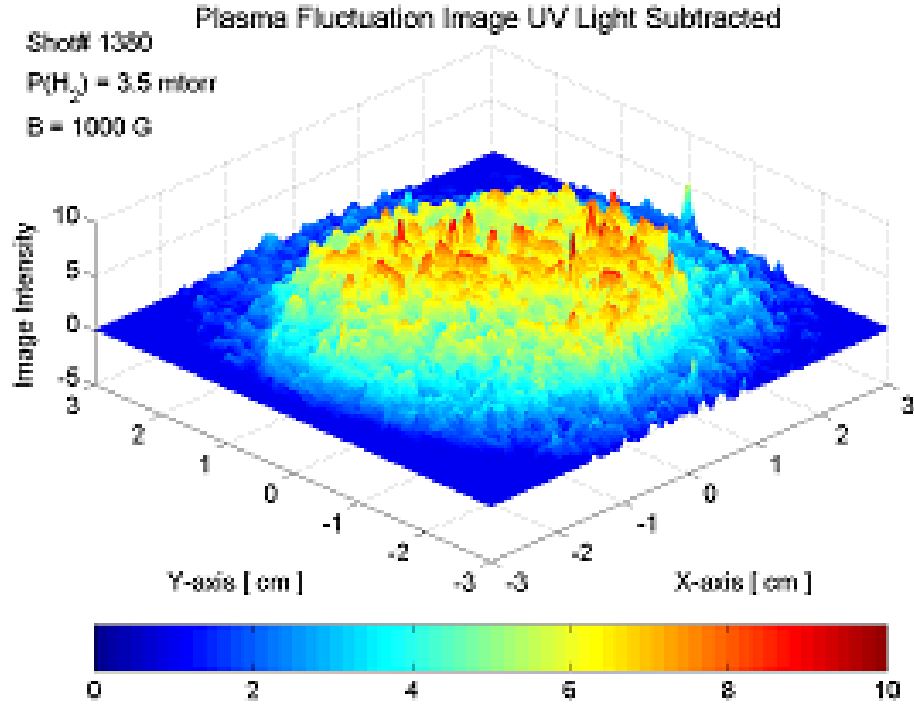


Fig. 12. A CCD camera image of the plasma excited CAPPIS diagnostic taken with a  $1 \mu\text{s}$  exposure time. The image is plotted as a false color 3D plot and the amplitude distribution and spatial structure of the plasma cross section are evident. ( $kT_e = 10 \text{ eV}$ )

### Investigation of Plasma Rotation and Shear

The experimental research conducted on plasma turbulence and coherent modes has shown that plasma fluctuations are influenced by the space potential and the presence of plasma rotation. In order to fully understand the cause and effect of these fundamental plasma characteristics we have developed new diagnostic probes and spectroscopic imaging techniques for measuring the radial electric field and spatial dependence of the plasma rotation frequency.

#### **Diagnostic measurements for space potential and rotation**

Advances in plasma probe techniques have helped improve the understanding of turbulent fluctuations and their role in transport processes. The following contains a summary of new diagnostic capabilities and goals.

**DC Emissive Probe:** Measurements of radial plasma space potential profiles have been performed in helium and hydrogen plasmas using a DC emissive probe diagnostic in

PISCES-A. The emissive probe circuit is designed to keep a constant emissive tungsten filament temperature and allow repeated sweeping of the applied bias voltage to obtain current-voltage characteristics at each spatial point. An inflection-point technique [ N. Hershkowitz, *Rev. Sci. Instrum.* **50** (1979) 210 ] is used to obtain the space potential at each point and thus determine the radial electric field profile, Fig. 13.

**Multi-tip Langmuir Probes:** Two types of multi-tip Langmuir probes were developed to measure plasma fluctuations and rotation. The measurements were performed in two different ways: The first is by taking advantage of three floating potential probes separated radially and poloidally. They yield the poloidal and radial electric fields and thus the  $\mathbf{E} \times \mathbf{B}$  velocity. The second probe has three ion saturation current tips that are also poloidally and radially separated giving the fluctuation velocity when the three channels are cross-correlated. A detailed radial profile of both velocity components ( $r, \theta$ ) have been obtained showing non-monotonic features outside the plasma in agreement with a complex dynamics of turbulence in this region which may be causing convective transport.

**Spectroscopic Imaging:** A new  $512 \times 512$  pixel CCD imaging camera has been fitted to a high resolution optical spectrometer in order to investigate plasma rotation in the PISCES-A plasma. This new diagnostic technique has determined the plasma rotation frequency from Doppler shift profiles contained in the  $\text{He}^+$  emission line. The chord-averaged measurement enables us to compare the results with the emissive probe and multi-tip Langmuir probes. Differences in the rotation frequency between different diagnostics will determine the contribution to rotation caused by other sources (e.g. Diamagnetic Drift).

**CAPPIS Imaging:** Our cathodoluminescent phosphor plasma imaging system (CAPPIS) has also detected plasma rotation. Spatial coherence analyses between Langmuir probe density fluctuations and the CAPPIS signal recorded with high bandwidth (10 MHz) photodiode detectors give rotation frequencies consistent with results obtained from the emissive probe and spectroscopic imaging. The fluctuating phosphor light also contains information on the coherent mode frequencies and knowledge of the plasma rotation frequency enables accurate determination of the exact frequency shift.

## Experimental Results

Plasma rotation and shear: Results from the new diagnostic techniques has provided us with a clear picture of the plasma rotation frequency profile. We have found that near the plasma core the plasma executes rigid rotation, and upon approaching the edge there is a steep change in frequency  $d\omega/dr \neq 0$ . The non-zero slope indicates the presence of shear and is very important in fully understanding the fluctuations in the edge region.

## References

J. Smith, N. Hershkowitz, and P. Coakley, Inflection-Point Method of Interpreting Emissive Probe Characteristics, *Rev. Sci. Instrum.* 50 (1979) 210.



A. Liebscher, S. Luckhardt, and S. Zweben, A Fast Phosphor Imaging Diagnostic for Two-Dimensional Plasma Fluctuation Measurements, (13<sup>th</sup> Topical Conference on High Temperature Plasma Diagnostics, June 2000).

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A. Liebscher, S. Luckhardt, G. Antar, and S. Zweben, A Fast Phosphor Imaging Diagnostic for Two-Dimensional Plasma Fluctuation Measurements, Rev. Sci. Instrum. 72, 953 (2001).

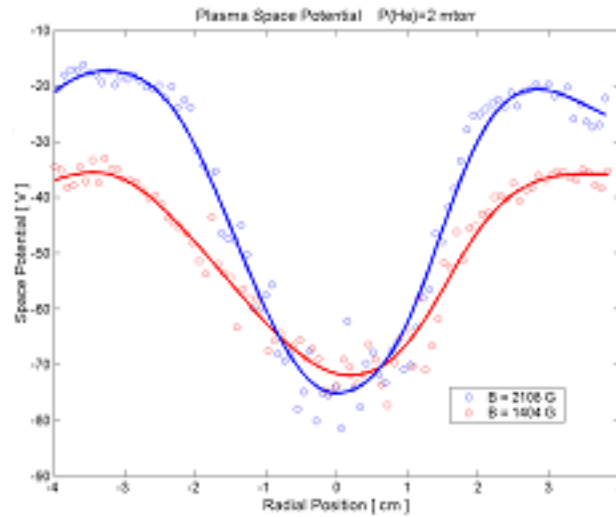


Fig. 13. Space potential profiles measured with a DC emissive probe diagnostic in hydrogen plasma. The potential profile shows a systematic flattening as the magnitude of the magnetic field decreases.

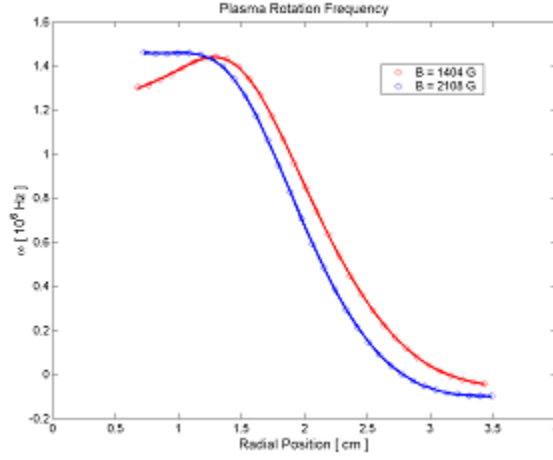


Fig.14. The rotation frequency  $\omega$  is plotted against the radial location within the plasma. Near the plasma core the average rotation is approximately constant, but further out at the edges there is a slope resulting in shear.

## Plasma Boundary Configuration Studies for the NCSX Stellarator

A. Grossman

The behavior of magnetic field lines outside the separatrix surface is considered to be an important subject in the edge physics of the stellarator. Magnetic field lines which connect the last closed magnetic surface and a target plate form a divertor configuration. Divertors are especially important for the stellarator, since they are designed to operate steadily and must achieve particle and energy balance under continuous fueling, and it is necessary to control this transport outside the last closed magnetic surface (LCMS).

Stellarators generally lack the ordered magnetic field line structure found in the scrape-off layer (SOL) of axisymmetric devices such as the tokamak. This is because the stellarator is an example of 3D MHD equilibria, for which it is mathematically not assured of possessing good flux surfaces, unlike the case for 2D. The individual features of this boundary layer need to be considered for vacuum vessel and plasma facing component design. A major challenge of this work is to utilize these unique features of the 3D SOL magnetics to achieve small angles of incidence and large wetted areas so as to distribute power loads uniformly. It is also necessary to achieve this goal with enough configurational flexibility, so these loads don't redistribute with changes in rotational transform, shear, beta, and other key parameters of the target equilibria. For most stellarators, it is sufficient to investigate the vacuum magnetic fields from the external coils alone to map out the underlying 3D magnetic topology in the SOL. In the case of

the National Compact Stellarator Experiment(NCSX), a major fraction of the rotational transform needed for stable equilibria is achieved by the bootstrap current which is a natural, undriven toroidal plasma current that arises because of the small aspect ratio and high beta needed to achieve compact design. Most other stellarators, such as the W7-X target a large aspect ratio and are optimized to zero out this current.

### **Magnetic Topology of Modular Stellarator with Bootstrap Current**

We have adapted the MFBE (Magnetic Field Solver for Finite Beta Equilibria) code developed by E.Strumberger at Garching to map out the magnetic topology of finite beta equilibria on a grid whose nodes may be arbitrarily close to the plasma boundary. The code has been modified using the virtual casing principle to permit accurate calculation of the magnetics in the case of a bootstrap current. The code requires a good free boundary equilibria, and we have modified it to use the latest VMEC2000 3D MHD equilibrium code, which provides the well converged free boundary equilibria used by the NCSX designers. The MFBE code uses several special empirical techniques, such as a nonequidistant integration mesh, to achieve high accuracy for the magnetics calculation in the SOL. This results in a calculation that is much more computationally intensive than in the more common vacuum magnetics calculation. The code is fully parallelized, with each processor of a 128 processor T3E devoted to each toroidal plane of the free boundary equilibria, which generally requires 1 hour of CPU time. The data transferred from the VMEC code includes the fourier coefficients of flux surfaces, and magnetic fields on flux surface, as well as the complete vacuum magnetic fields. After the magnetic fields are calculated everywhere, a line tracing is done using the Gourdon code. A magnetic field line is started at a specific location and followed toroidally for an arbitrary number of turns. The collection of intersections of a field line with a specific toroidal plane after many toroidal transits is termed a Poincare puncture plot, and provides a wealth of information about the topology of the magnetic field line. An example of the NCSX puncture plot from this calculation superimposed on the CAD drawings for NCSX is shown below. The first few intersections with starting points on the outside midplane at 0, 0.2, 0.4, 1.8 and 3.8cm are shown in the left side of the Fig. 15 below. The complete set of punctures for 60 field lines started uniformly between 0 and 2 cm from the LCMS on the midplane are shown in orange, superimposed on the CAD drawing of the NCSX vacuum vessel are shown in Fig 16.

#### **Findings:**

- There is a large flux expansion of more than 5 at the banana tips, which is useful for divertor design.
- There are island chains in the SOL, but these are not robust enough for an island divertor design.
- A stay-out zone of 2cm from the LCMS, where there would be a very short connection length to any object placed in this zone has been mapped out.
- The relative radial ordering of field lines are also preserved in this zone.
- Outside of this zone there are large radial excursions in only a few toroidal transits, and the field lines move in and out radially as they transit around toroidally.

- [1] A.Grossman, “Magnetic Field Topology of the NCSX Scrape-Off Layer: 1.4m Major Radius LI383 Plasmas” Presented at July 24-25, 2001 Project Meeting at PPPL.
- [2] B. Nelson, T. Brown, M. Cole, A.Grossman, P. Mioduszewski, “ NCSX In-vessel Engineering Design Update” Presented at July 24-25, 2001 Project Meeting at PPPL.
- [3] P. Mioduszewski and NCSX Plasma Boundary Group, “Status of Plasma Boundary Configuration Studies and Vacuum Vessel Design” Presented at July 24-25, 2001 Project Meeting at PPPL.
- [4] A.Grossman, E.Strumberger “Edge Magnetic Field Structure Study” Presented at July 13, 2000 Project Meeting at PPPL.
- [5] A.Grossman “Edge Magnetic Field Structure Mapping” Presented at Sept 27, 2000 Project Meeting at PPPL.
- [6] A.Grossman, “Edge Magnetic Field Line Structure in the Quasi-Axisymmetric Stellarator NCSX” Presented at October 23-27, 2000, APS-DPP Meeting, Quebec City Canada.

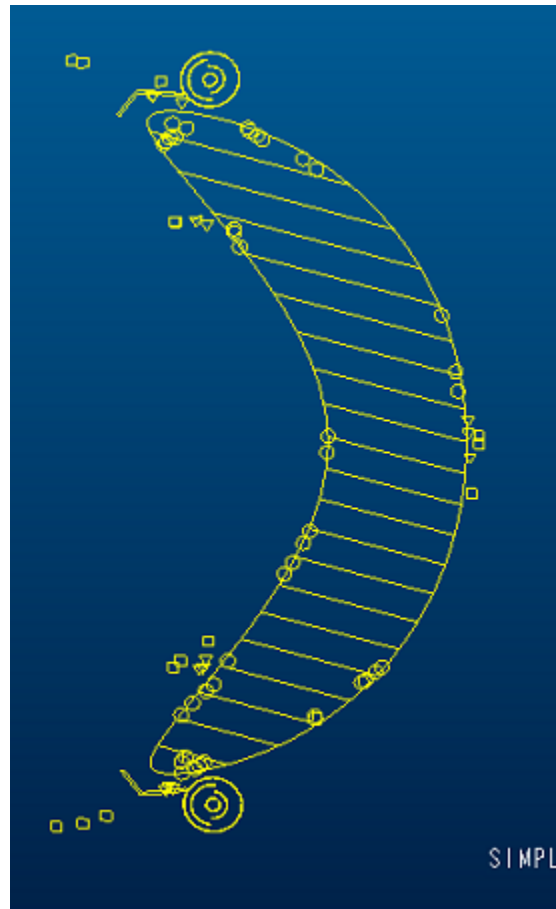


Fig. 15. The Li383 equilibrium at the 0 degrees “bean” cross-section, with the punctures from the first few toroidal turns (all three periods superimposed), with the starting points on this midplane at 0, 0.2, 0.4, 1.8 and 3.8cm from the LCMS

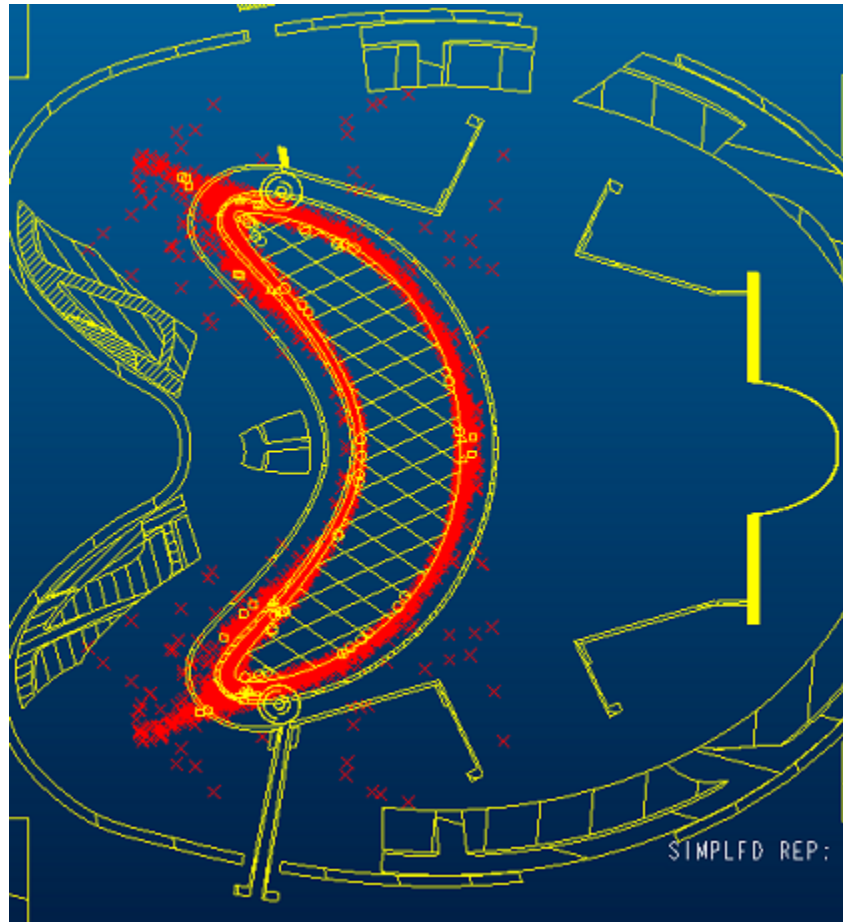


Fig. 16. NCSX boundary magnetic field line tracing vacuum vessel superimposed. It can be seen that a magnetic divertor may be formed at the tips of the equilibrium configuration.

Vacuum  
vessel

PFC  
panels

## Plasma Materials Interactions Experiments

The US ALPS/APEX/ALIST technology development programs have all focused attention the investigation of flowing liquid wall and interactive materials for magnetic fusion applications. Of the many options, liquid lithium is particularly interesting because of its low atomic mass, and the expectation that it will provide a low-recycling boundary for hydrogen isotopes and impurity atoms such as oxygen, carbon and others.

During the past year we have carried out experimental investigations using the PISCES-B facility on plasma interactions with liquid lithium, These experiments are aimed at the problem of quantification of the influx rate of lithium into the plasma as a function of temperature and the problem of hydrogen isotope retention and recycling. Our results in liquid lithium research, from the past year, are reported below. The work is organized into four research thrusts: (1) Plasma erosion of lithium, (2) Surface recombination of hydrogen on Li, LiD liquids, (3) Hydrogen retention rate of liquid lithium, (4) Permeation and diffusion of hydrogen in liquid lithium.

### Liquid Lithium Plasma Interactions

This section is devoted to the issue of lithium influx rate measurements and their temperature dependence. Over the past few years, extensive temperature scaling experiments on PISCES B revealed for the first time an anomalous increase in lithium erosion rates at high temperature, Fig. 17.

The principal results from the liquid lithium plasma erosion experiments on PISCES are:

- Enhanced erosion rates of liquid lithium are observed during deuterium plasma exposure. The enhanced erosion rate ranges up to one order of magnitude greater than the present physical sputtering theory prediction.
- Enhanced erosion regime discovered for liquid metals. Doerner scaling of erosion shows  $\Gamma_{\text{liquid}} \sim \exp((T-T_{\text{mp}})/50\text{K})$ .
- Lithium self-sputtering is less than unity for these plasma exposure conditions.

Over the past year we have examined several potential explanations for the Doerner effect including: (1) Critical temperature scaling of the surface binding energy in a liquid metal, (2) Near surface stratification, (3) Thermal spike evaporation enhancement, (4) Bubble formation. As yet none of these models has been shown to fully explain our observations. We will continue these investigations in the coming year examining other models and refined versions of the above mentioned models.

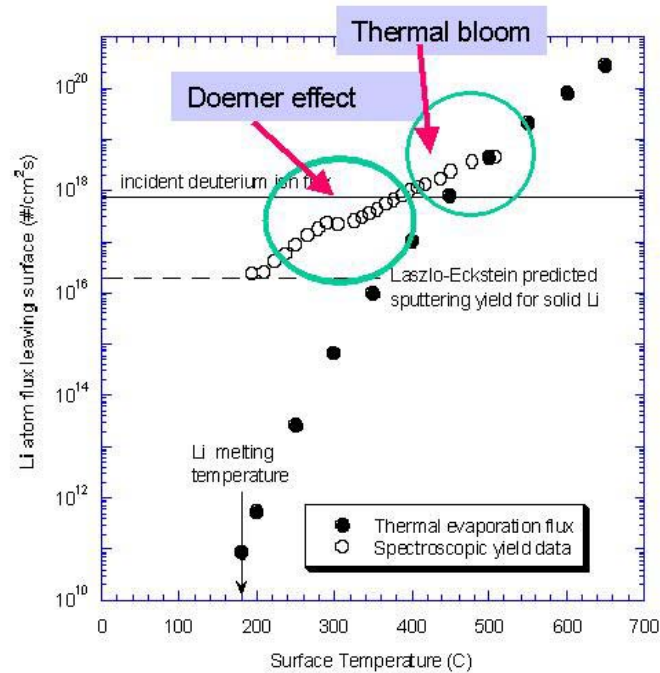


Fig. 17. Lithium atom flux eroded from liquid lithium material sample in PISCES-B indicates enhanced flux beyond that predicted by the TRIM (Lazlo-Eckstein model).

### Hydrogen Surface Recombination Experiments on Liquid Lithium

Assessment of liquid lithium for particle removal in a first wall environment relies on the determination of fundamental properties such as diffusivity, surface atom recombination in the case of hydrogen isotopes and retention. Currently the literature reveals a wide range of diffusivities for hydrogen in liquid lithium and measurements of the other properties are scarce, especially for He.

- Surface recombination of D atoms on molten Li:** During FY01 we carried out measurements of the rate of recombination for deuterium atoms on the surface of various molten solutions of Li–LiD using thermal desorption spectrometry (TDS). Recombination rates were found to follow an Arrhenius relationship in the temperature range 300 – 600° C as shown in Fig. 18. These results are lower than predicted by the kinetic model of Pick and Sonnenberg (*J. Nucl. Mater.* **131**, 1985) by a factor of ~25 and can be explained by a reduced surface site availability due to surface contamination, which is always present with this type of measurement. With a surface site availability of 4% the data and model agree well. The significance of this work lies with the verification of the applicability of the kinetic model, which previously had only been applied to solids. This work was conducted in collaboration with Dr. Causey of Sandia National Laboratory and has been prepared for submission to *Phys. Rev. Lett.*



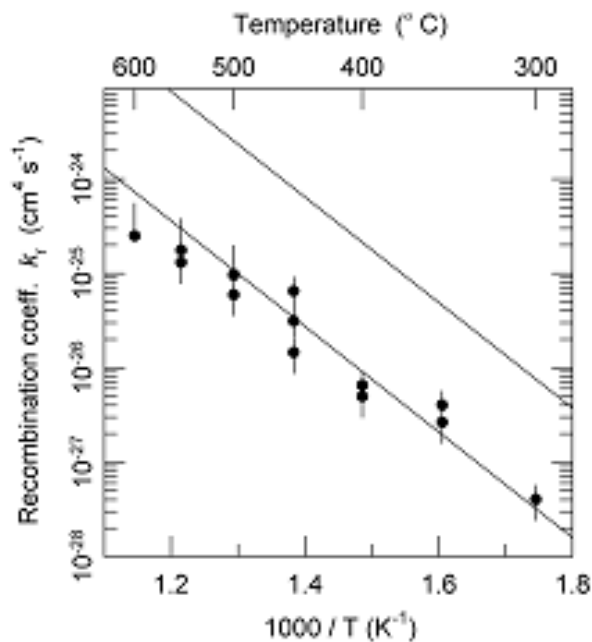


Fig. 18. Recombination rates plotted as a function of reciprocal temperature. The lines are the prediction of the Pick and Sonnenberg model. Upper line – full surface site availability. Lower line – 4% surface site availability.

### Hydrogen Retention Measurement in Liquid Lithium

- Measurements of the retention of deuterium in liquid lithium were made for samples exposed to deuterium plasma in PISCES-B. Retention was determined using TDS for samples exposed to plasma  $D^+$  ion fluences in the range  $10^{19}$ – $2 \times 10^{22} \text{ cm}^{-2}$  as shown in Fig. 19. The results reveal full absorption of all deuterium ions incident on the liquid lithium surface until the sample is completely converted to lithium deuteride. Additional retention (points consistently indicate more than 100% retention) is believed to be a result of reaction of the lithium with neutral atoms since molecular species were found not to be significantly absorbed under the conditions of these experiments. This work is currently being prepared for submission to *J. Nucl. Mater.* In FY02 He retention will be explored.

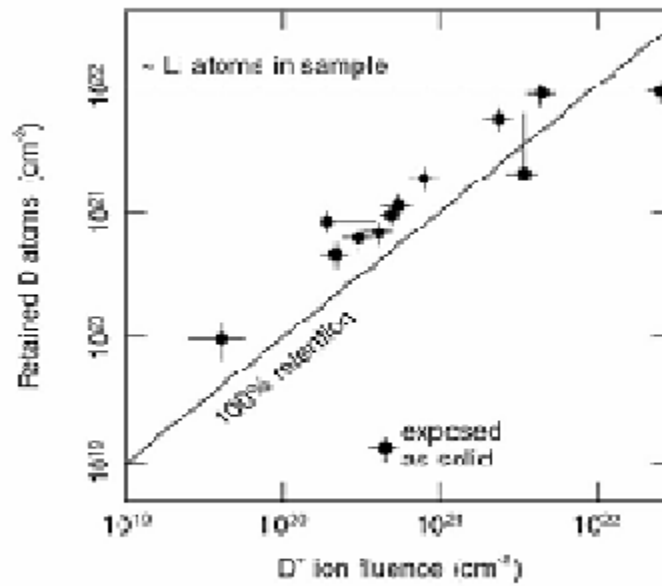


Fig. 19. Retention of deuterium in liquid lithium as a function of plasma D<sup>+</sup> ion fluence is found to be essentially 100%. The dashed line shows the number of lithium atoms in samples and the full line indicates 100% retention of deuterium ions. Solid Li samples show lower hydrogen retention rates.

## Helium and Hydrogen Permeation Measurements in Liquid Lithium

- Methods were established for producing a liquid metal vacuum seal for permeation experiments, as shown in Fig. 20a,b. Permeation experiments were undertaken with He gas (a) and plasma (b) exposure of one side of the liquid metal seal while pumping on the other and monitoring for permeation with a residual gas analyzer (RGA). Results have been difficult to obtain for He owing to its low solubility in liquid lithium, which leads to a permeation flux below the detection limit of our current system. However, preliminary experiments with deuterium gas suggest that measurement of the diffusivity of D in liquid Li ought to be possible. These experiments will continue in FY02.



Fig. 20a. Images of the liquid lithium seal: (a) in helium gas and (b) in helium plasma.



Fig. 20b. The under side of the liquid metal is pumped (through the support tube) with an RGA.

## **Innovative Plasma Facing Systems**

The experience gained with liquid metals plasma interactions by PISCES Laboratory personnel is benefiting other aspects of the U.S. Program. As was previously reported, the PISCES group carried out the development, design, and fabrication of a liquid lithium rail limiter, L3 during FY2000. This limiter is now deployed in the CDX-U torus device at PPPL, and lithium limiter experiments are ongoing.

The development of this limiter required several new experimental techniques for use of liquid lithium in the plasma environment. These included these developments:

- Reliable hydraulic piston and flow system for liquid lithium transport in vacuum.
- Novel techniques to bond liquid lithium to stainless steel substrates.
- Lithium wetting techniques for creating large area continuous liquid lithium surfaces.
- An internal heating system for maintaining the liquid surface temperature.
- A remote control positioning arm to accurately place the limiter in contact with the plasma.

The liquid lithium rail limiter designed and built by the UCSD PISCES group has the following design features.

- The rail limiter can be introduced or removed from CDX-U through a port without breaking vacuum
- The lithium on the rail limiter may be presented to the plasma in either solid or liquid form depending on the needs of the particular experiment.
- A paper [1] is in preparation describing the details of the rail limiter design.
- A paper [2] is in preparation describing plasma experiments on CDX-U using this new Li rail limiter.

## **Publications**

[1] R. P. Seraydarian, L. Chousal, R. P. Doerner, M. Baldwin, S. C. Luckhardt, T. Lynch and R. W. Conn, to be published.

[2] G. Y. Antar, et al., to be published.

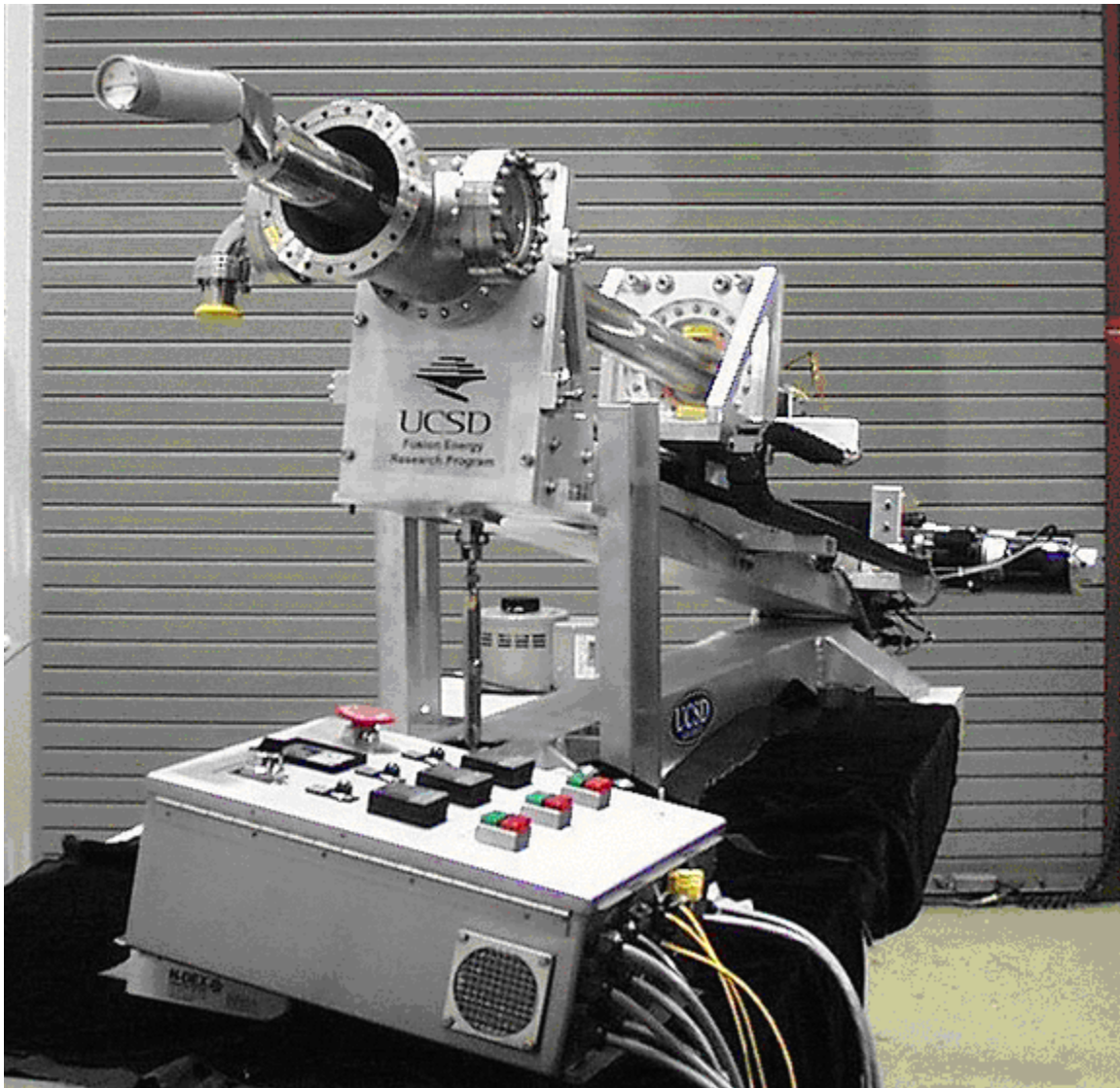


Fig. 21. UCSD fabricated the CDX-U Liquid Lithium Limiter, here shown in near-full assembly. The lower surface of the limiter head (upper left in photo) is the only part that actually contacts the plasma.

## UCSD/PPPL L3 Rail Limiter Experiments

In the section of “Innovative plasma-facing systems” of the last three-year renewal report, the PISCES group described the lithium limiter that is installed on CDX-U spherical torus. [1] We report here the first results on plasma-liquid lithium interaction experiments that we carried out on the PPPL CDX-U torus[2].

The CDX-U plasma was started up in these experiments after conditioning and wall preparation. The preparations consisted of (1), the limiter cleaning by argon glow discharge and (2) wall coating by titanium gettering. Afterwards, we were able to maintain plasma conditions unchanged during the whole day, that is, for about 40 shots. Plasma operation was not adversely affected by the presence of the liquid lithium limiter.

The main results can be summarized in three points:

- We did not record any disruption related to the liquid lithium present in the vacuum vessel. We had a whole week with the same conditions, which permitted substantial data collection on the plasma-lithium interaction.
- During the plasma operation, liquid lithium droplets (LLDs) were observed to intermittently detach from the limiter. A detailed study of the forces acting on the lithium revealed that this is caused by the magnetic forces caused by body currents flowing to ground through the limiter. The size of the lithium droplets and their velocities were estimated using a fast imaging camera.
- A detailed investigation of the plasma edge properties with or without the lithium limiter revealed that it does not change significantly. This is actually in agreement with calculations predicting the amount of change as the limiter is inserted with respect to reproducibility of the plasma discharges and the level of turbulence. In conclusion of this result, we recommend a larger area of interaction with the lithium something already under development.

In the near future, more experiments using two cameras looking with two different angles will enable us to follow in more details the trajectory of the lithium droplets. Furthermore, by installing a light filter centered on hydrogen excitation, we aim at evaluating the hydrogen content in these droplets.

Another experiment will be conducted with the lithium limiter floating instead of grounded. The purpose is to evaluate the presence of lithium droplets. This type of experiment could be crucial for future limiter designs of plasma-facing liquid lithium set-up. A set of experiments with the toroidal liquid lithium tray will also be conducted in order to assess the effects of the liquid lithium on the plasma confinement. This work is performed in collaboration mainly with R. Kaitia and R. Majeski (PPPL).

## References:

- [1] R. Saradayan, L. Chousal, R. P. Doerner et al., to be submitted to Fusion Engineering and Design
- [2] G. Y. Antar, R. P. Doerner, R. Kaita et al. submitted to Fusion Engineering and Design.

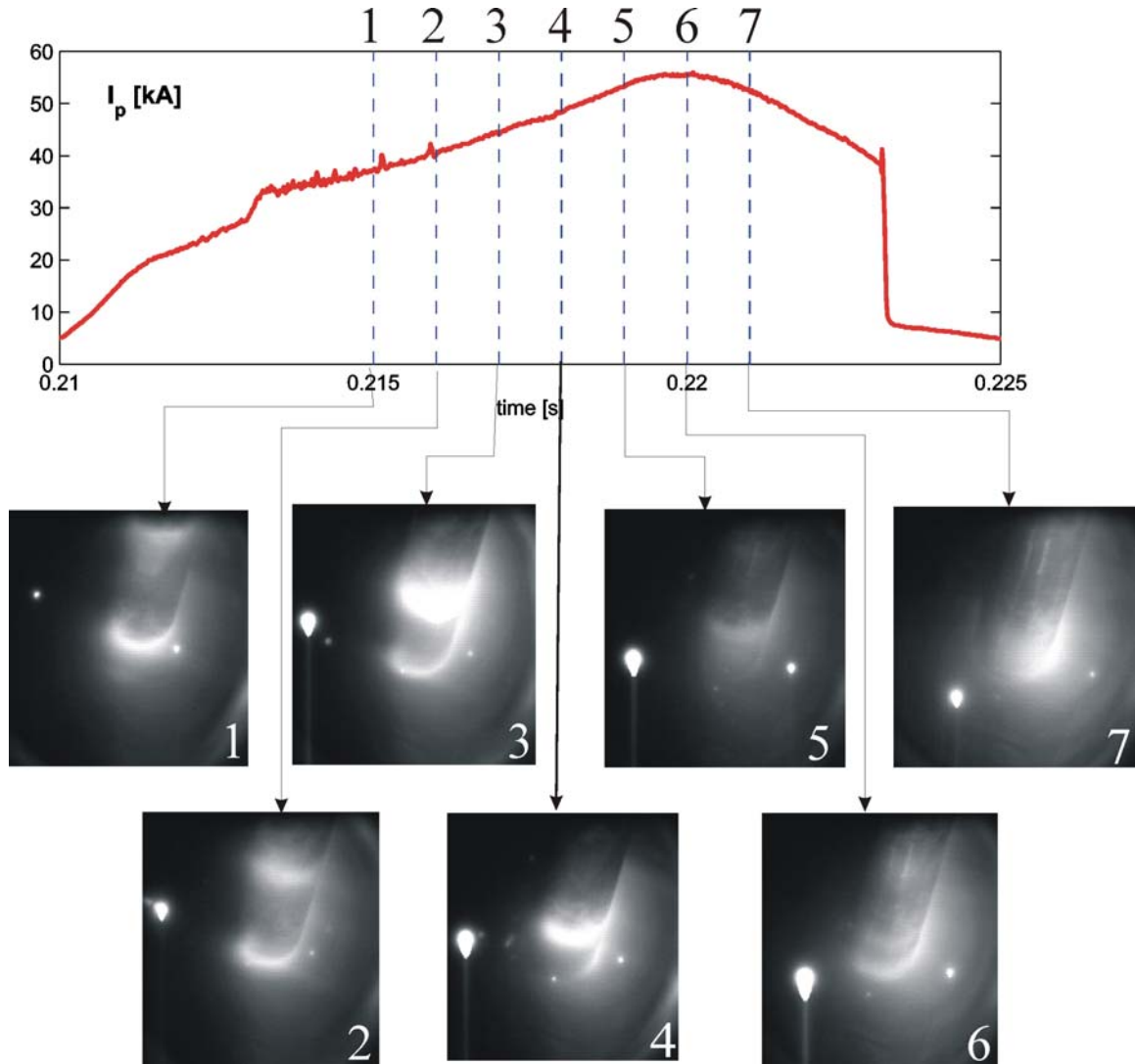


Fig. 22. This figure shows snapshots taken by the fast camera with 1 ms interval. The camera is looking to the limiter from below at an exposure time of 50  $\mu$ s. This figure shows that the plasma-lithium interaction is not stationary and presence of liquid lithium droplets (LLDs) in the plasma. The LLDs do not appear to be falling freely but rather follows the field line suggesting that it is entrained in the plasma flow.

## **Carbon Tungsten Beryllium Materials Studies**

At the time of this writing, we are continuing work on understanding of tungsten materials interactions. During the past year we found the first evidence of surface damage (i.e., blisters and pits) of tungsten surfaces exposed to low energy plasma fluxes in PISCES [F.C. Sze et al., J. Nucl. Mater. 264 (1999) 89, F.C. Sze et al., J. Nucl. Mater. 266-269 (1999) 1212]. This result is significant since it may lead to additional influxes of tungsten dust to the edge region, and to surface damage of tungsten plasma facing systems.

Carbon materials behavior continues to be a focus of materials interactions research. Recently, the hotly debated issue of the flux dependence of chemical erosion was investigated under well-controlled plasma conditions in PISCES. These well-diagnosed exposures proved trends previously attributed to a flux dependence were more likely due to the variation of ion energy with increasing flux and the previously unmeasured density dependence of the photon efficiency [D.G. Whyte et al., submitted for publication to J. Nucl. Mater. (2000)]. While there are still unanswered questions concerning the demands placed on plasma-facing components in next-generation large confinement devices, the PISCES Program continues to provide valuable measurements and insights into their designs.

## **Boron Coatings on Graphite**

The glow discharge technique has been used in magnetic confinement devices to produce protective films and has been critical in providing sufficient wall conditions that have lead to the discovery of enhance operating plasma regimes (e.g. VH-mode on DIII-D). However its slow deposition rate severely limits its application frequency and efficacy. This has motivated interest to develop new and more efficient means of producing boronized surfaces in tokamaks.

## **Carborane Plasma Deposition of Boron Coatings on Graphite and Other Materials**

During the past year, we carried out experiments to test the efficacy of carborane gas plasma deposition as a boronization technique for tokamaks. The experiments were performed at the UCSD PISCES-B facility in a collaborative format with UCSD, GA-DIII-D, PPPL-NSTX.



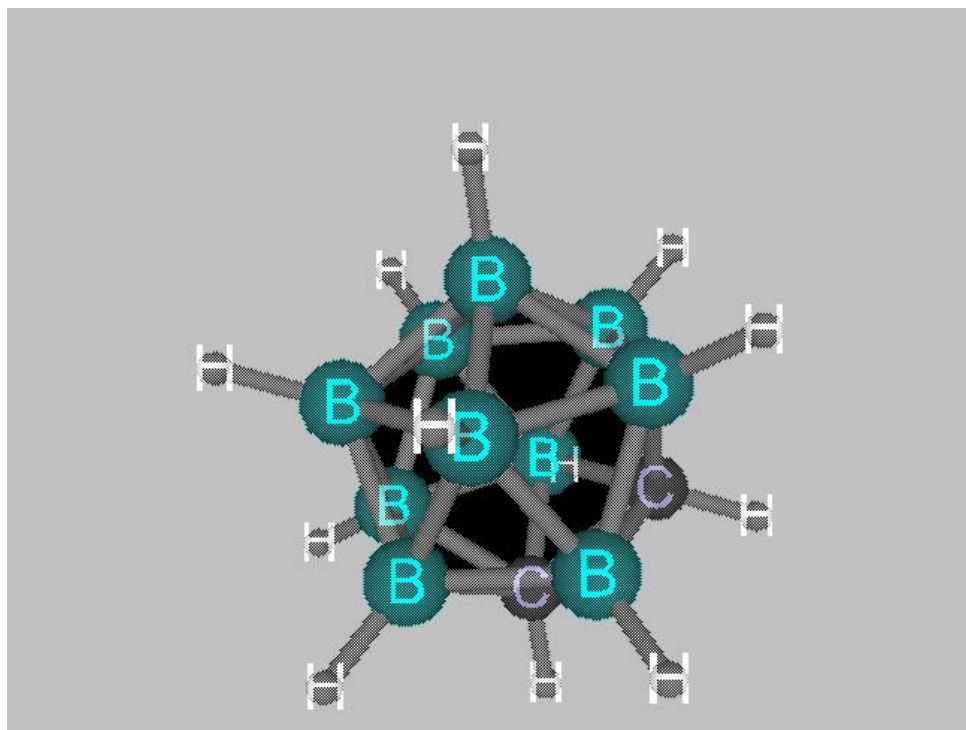


Fig. 22. Carborane is an icosahedral molecule ( $C_2B_{10}H_{12}$ ) with a very high boron to carbon ratio of 5:1.

Injection of carborane ( $C_2B_{10}H_{12}$ ) into the PISCES-B plasma was found to produce boron (B) containing films on various target species. Significantly, the film growth rates achieved are extremely high (up to 30 nm/s, see Table) compared to those typically found for glow discharges ( $< 0.1$  nm/s).

Target	Sample T (°C)	Carborane rate ( $\times 10^{17}$ molecules/s)	Film depth (nm)	Film growth rate (nm/s)	Relative growth rate to ion flux	Global efficiency	B/C ratio in film
C	250-400	1.5	3500	33	1.25	0.73	3
Al	430	1.5	$2 \times 10^4$	11	0.4	0.24	3.6
Al	400	1.5	2000	17	0.54	0.37	3.2
W	200	1.5	0	—	—	—	—
W	200	18	250	2	0.06	0.004	N/A
W	80-150	3.8	0	—	—	—	—
W	60-150	13	400	12	0.33	0.03	9.3

**Table 1** Summary of boron film deposition using carborane on PISCES-B. Plasma conditions: incident ion flux  $\sim 3 \times 10^{21} \text{ m}^{-2}\text{s}^{-1}$ , electron temperature  $\sim 40$  eV.

For low-Z target materials (C and Al) the film production is highly efficient, with the boron film growth rate comparable to the incident ion flux and the injection rate of boron atoms Fig. 24. The boron to carbon ratio is  $\sim 4:1$  for the film. Similarly high growth rates ( $\sim 10$  nm/s) are obtained with a high-Z target (W), but with lower deposition efficiency and higher B/C film ratio.

The experimental results are found to agree with a simple model based on the implantation, reflection and re-erosion of B-containing molecular ions at the targets, which are inferred to contain  $\sim 6$  B atoms per molecule. The high film growth rate/efficiency are apparently linked to the high degree of carborane ionization and dissociation caused by the  $\sim 40$  eV PISCES-B plasma, compared with  $T < 1$  eV plasmas of glow discharges.

This technique shows that it may be possible to continuously produce protective boron films in magnetic confinement fusion devices where net erosion rates approach 10 nm/s. This would greatly enhance the impact of boronizations on issues such as impurity control and wall conditioning. For instance, on PISCES the injection of carborane was found to have an immediate beneficial effect on vacuum/plasma purity, Fig. 25.

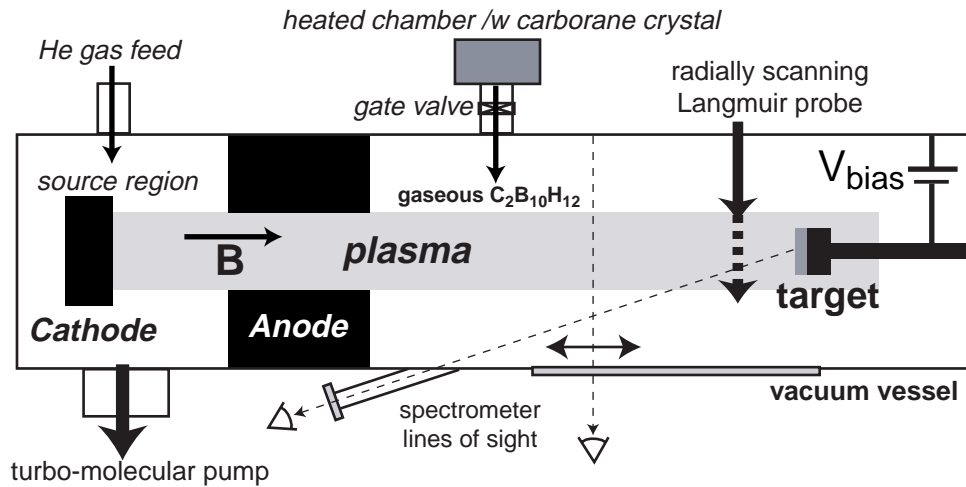


Fig. 23. Schematic of carborane film deposition experiments in PISCES-B

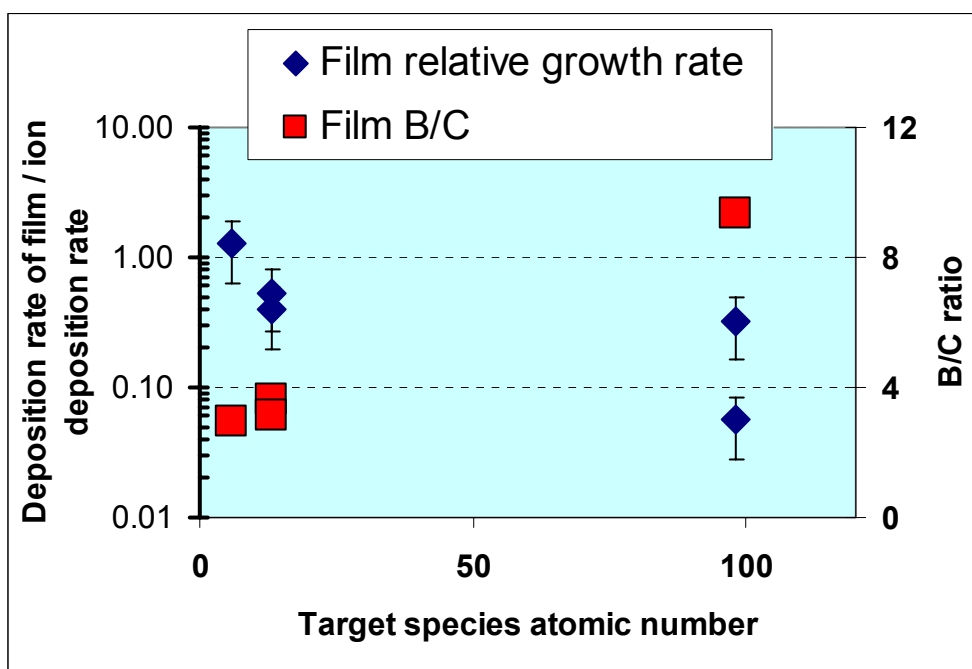


Fig. 24. For low-Z targets like graphite, the film deposition rate actually exceeds the ion deposition rate, indicating that polyatomic molecular ions are responsible for the deposition. The boron to carbon ratio of 4 is close to the carborane molecular ratio of 5.

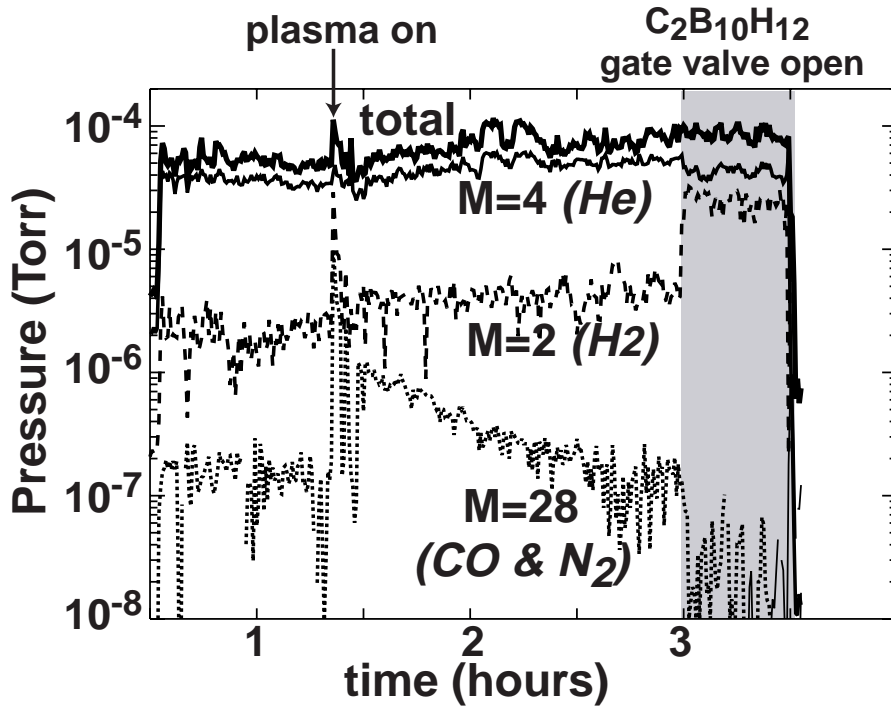


Fig. 25. After an atmospheric vent, the PISCES plasma cleanliness (indicated by mass 28) recovers on a time-scale of hours. With the injection of carborane, the plasma immediately recovers its pre-vent cleanliness.

## Collaborative Research Programs

PISCES is uniquely suited to advancing the understanding of plasma-solid interaction with a complete set of plasma and surface diagnostics. The PISCES plasma exposure parameter range and the steady state nature of the plasma source allow for realistic testing of solid materials for the demanding environment of Next-Step magnetic fusion confinement devices. The knowledge gained in PISCES is efficiently communicated and transferred to the global fusion community. This effective cooperation and transfer is effectively supported through our collaborations with other PMI groups, confinement devices, and interactions with modelers. The major collaboration programs planned for the next three years include:

### US-Japan Collaboration

- Investigation of molecular ion effects on plasma recombination and materials interactions with NIFS LHD and Nagoya University NAGDIS groups.
- Investigation of boron coatings on tungsten, NIFS LHD.
- Investigation of plasma erosion of tungsten and non-linear effects such as blister formation. Kyushu University.

### **US-ALPS-APEX-ALIST and PPPL Collaborations**

- Carry out collaborative investigations of liquid metal plasma facing systems on the CDX-U torus. Collaborative partners, PPPL and the US ALPS program.
- Improved understanding of boronization film deposition will be of general interest to world fusion community due to the widespread use of this technique.
- The NSTX program will study the results of the carborane boronization trials on PISCES-B to decide on its implementation for NSTX.

### **Collaboration with UCSD Theory Group.**

The UCSD theory group under the leadership of Prof. Krashinennikov has begun an effort to develop and validate plasma boundary theory and modeling, with support from the OFES theory program. Interaction with the PISCES experimental program is plan during the next three years including the following tasks:

- Atomic and molecular radiative and kinetics in PISCES using Pigarov CRAMD model. Validate molecular ion modeling.
- Neutral gas transport in PISCES: Physics and chemistry using CRAMD and NTNG neutral transport neutral gas model.
- Modeling of turbulence and anomalous plasma transport in PISCES using the 2D and BOUT codes.